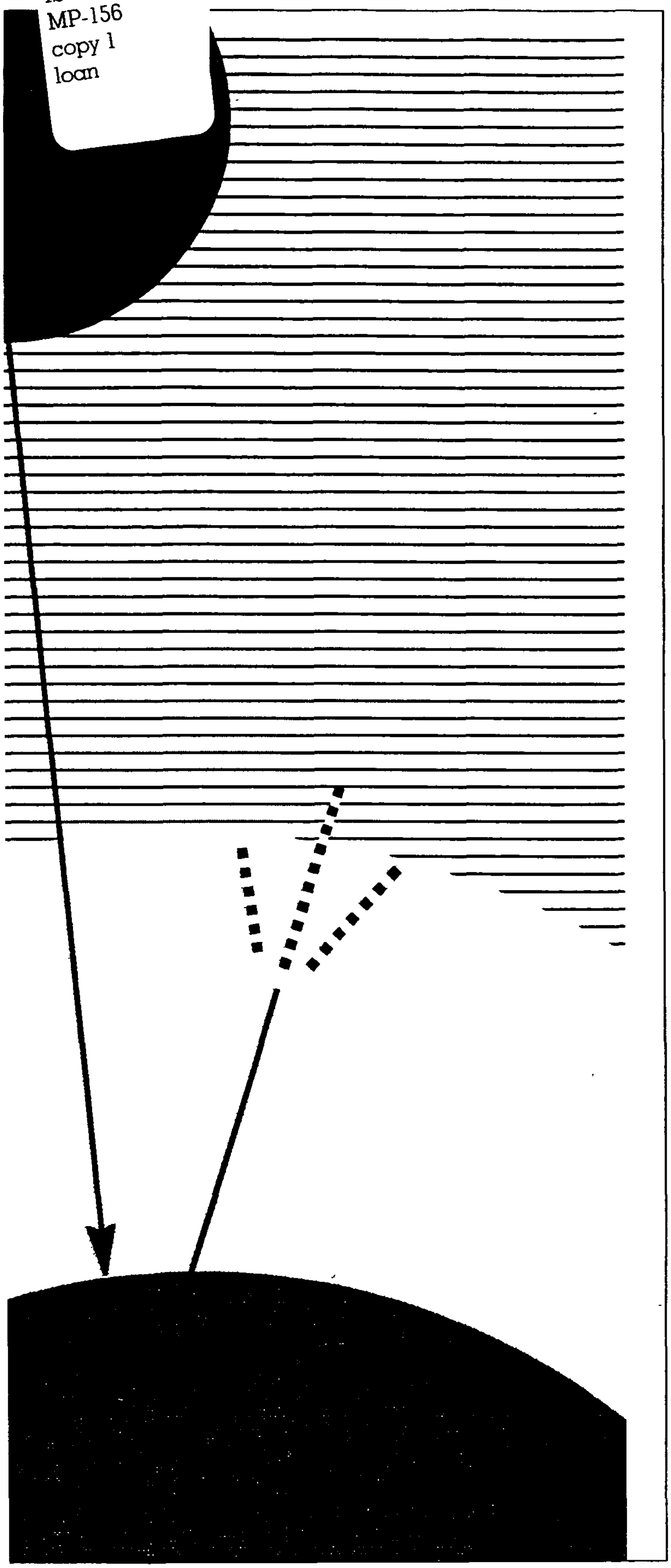

What Is and Is Not Known about Climate Change in Illinois: The Scientific Perspective

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Illinois State Water Survey
Champaign, Illinois

May 1994
Miscellaneous Publication 156

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INTRODUCTION

This document summarizes previously published findings from various studies concerning 1) the potential future climate conditions for Illinois, and 2) the possible range of physical effects, economic impacts, and adjustments related to future changes in the state's climate. This document prepared in mid-1993 attempts to identify what is and is not known about the climate change issue as it relates to Illinois.

Among the many problems now facing the environment, potential global warming due to global burning of fossil fuels, and the resultant greenhouse effect, rank at the top. Currently, fossil fuels supply about 80 percent of the energy we generate for heating and cooling in Illinois. While a general warming trend may not be too serious in itself, accompanying shifts in the amounts and distribution of rainfall and snowfall, changes in the levels of the Great Lakes, and the possibility of a forced change in the distribution biota such as forests, row crops, and wildlife would challenge the resourcefulness and resiliency of future generations (Changnon, 1989a, 1989b).

Accurate predictions of exactly how these climate changes will evolve or their ultimate magnitudes would allow us to better prepare. The physical system that determines our climate is very complex, and current global climate models cannot simulate either present or future conditions adequately, especially on a regional scale such as for Illinois. And scientists are postulating some climate changes that would result in significant changes in our lives.

The global warming-climate change dimension, and its potential effects on Illinois, are only partially defined. There are questions about whether global warming will occur. Most atmospheric scientists agree with the predictions of the general circulation models (GCMs), which indicate that ever-increasing carbon dioxide (CO_2) and other trace gases will ultimately lead to global warming. Other atmospheric scientists disagree, however.

A 1992 sampling of atmospheric scientists in Illinois and Indiana revealed that 80 percent believed that global warming would occur, and 50 percent believed that it had already begun (Changnon et al., 1992). A similar Delphi sampling in 1990 of 62 climatologists actively involved in global climate change research indicated that 80 percent were convinced that a significant climate change would occur due to anthropogenic gases (Slade, 1990).

By assuming that global warming is occurring, uncertainties arise as to the distribution of areas of greater or lesser degree of change in Illinois. Even ardent believers in climate change carefully qualify their statements because GCMs are unable to define *regional* climate values (Rind, 1989; Kalkstein, 1991). This inability to specify present and therefore future regional conditions makes it difficult to assess possible changes on the physical systems such as water resources, as well as potential economic impacts (Ausubel, 1991a).

Nevertheless, the potential seriousness of global warming is sufficient that over the past several years certain policy makers at the national and international levels have been actively considering ways to reduce the emission of radiative gases on a global scale. Therefore, it would be beneficial for policymakers at all levels (local, state, federal, and international) to obtain estimates of the potential effects of climate change before making major policy changes with significant economic impacts on Illinois. Given future climate uncertainties due to trace gases, the basic approach of impact analysis has been to use a range of "climate scenarios" and estimate potential effects for each "sensitivity analyses".

The report begins with information about anthropogenic alterations or human effects on the weather and climate of Illinois. The next section explains the Illinois climate, including its causes, and describes how the greenhouse effect could change it. Various scientific views are presented about the potential for climate change. Another section describes the "climate scenarios" that have been generated, both from GCMs and from historical analogs, and used to define possible future climate conditions. The final sections present the possible effects of future climate scenarios on water resources, agriculture, and other sectors in Illinois. There is also an assessment of findings from studies of the potential means of adaptation to climate change in Illinois. The summary reviews what is and is not known about climate change.

HUMAN EFFECTS ON WEATHER AND CLIMATE

For more than 200 years, scientists have speculated about the impact of human activities (including land-use changes and the emission of pollutants to the atmosphere) on weather and climate. Thomas Jefferson was one of the first Americans deeply interested in the nation's climate. In 1780, he wrote, "A change in our climate is taking place. Both heat and cold are becoming much more moderate and snows are less frequent and less deep. Winds from the east and southeast have advanced into the country. As the lands become more cleared, it is probable that the winds will extend further westward" (Martin, 1956). Land clearance and its effects on climate became a major topic of discussion along the eastern seaboard of the United States and in Europe as a result of Jefferson's findings.

Almost 100 years later, a noted meteorologist of the mid-19th century presented opposing views. Elias Loomis, professor of Natural Philosophy at Yale College, stated, "The climate of a country remains permanently the same from age to age. It is not certain that the climate of any country, in any of its aspects, has changed appreciably in the past 2000 years. The destruction of forests changes the water cycle, but these changes do not seem to affect the mean temperature of any place or the annual amount of rain" (Loomis, 1868).

Thus, without much data or sophisticated methods of analysis, some early speculation suggested that the climate shifted as a result of human changes in land use. Others speculated that anthropogenic generated changes in climate were not possible.

By the end of the 19th century, European scientists had swung back to the opinion of Jefferson because they had finally measured the localized differences in climate conditions due to European cities and rural land-use changes (Landsberg, 1970). Similar studies began in the United States in the 1960s. Changnon (1973) identified how a variety of human activities, including land clearing, drainage of large wetland areas, industrial emissions, and the development of large urban areas, had altered local and regional climatic conditions over the last 200 years. Subsequent intensive meteorological studies of urban areas in St. Louis and Chicago revealed changes in every aspect of these cities' local climates including temperature, wind, rainfall, and storminess (Changnon, 1978). Table 1 displays the rate of temperature increase over a 100-year period at four major U.S. cities. This amount of change over 100 years in the mean temperatures of these four cities is of the same magnitude as predicted when CO_2 is doubled (Changnon, 1992c). Figure 1 shows the changes in summer precipitation in St. Louis as a result of human activities. The areas of increased rainfall and storminess are permanent features of the climate in St. Louis and east of the city.

Table 1. Rate of Temporal Increase of Mean Temperature at Selected Cities as Excess over Rural Increases, in Degrees Fahrenheit during the Last 100 Years.		
City	**Winter**	**Summer**
Cleveland	1.8°F	5.0°F
Boston	2.9°F	4.7°F
Washington, DC	1.6°F	4.3°F
St. Louis	2.2°F	5.0°F

Other human activities such as emissions from jet aircraft have produced changes in cloud cover and air quality over regions larger than Illinois. These activities have reduced visibility, moderated the difference between day and night temperatures, and altered the amount of rainfall (Changnon, 1981a, 1987a).

Extensive research has firmly established that human activities, including land-use changes and emissions to the atmosphere of moisture, gases, and particulates, have altered local and regional climates, some significantly and others only slightly. These findings have served as the basis for believing in alteration of climates on a global scale due to worldwide increases in the emission of trace gases from human activities.

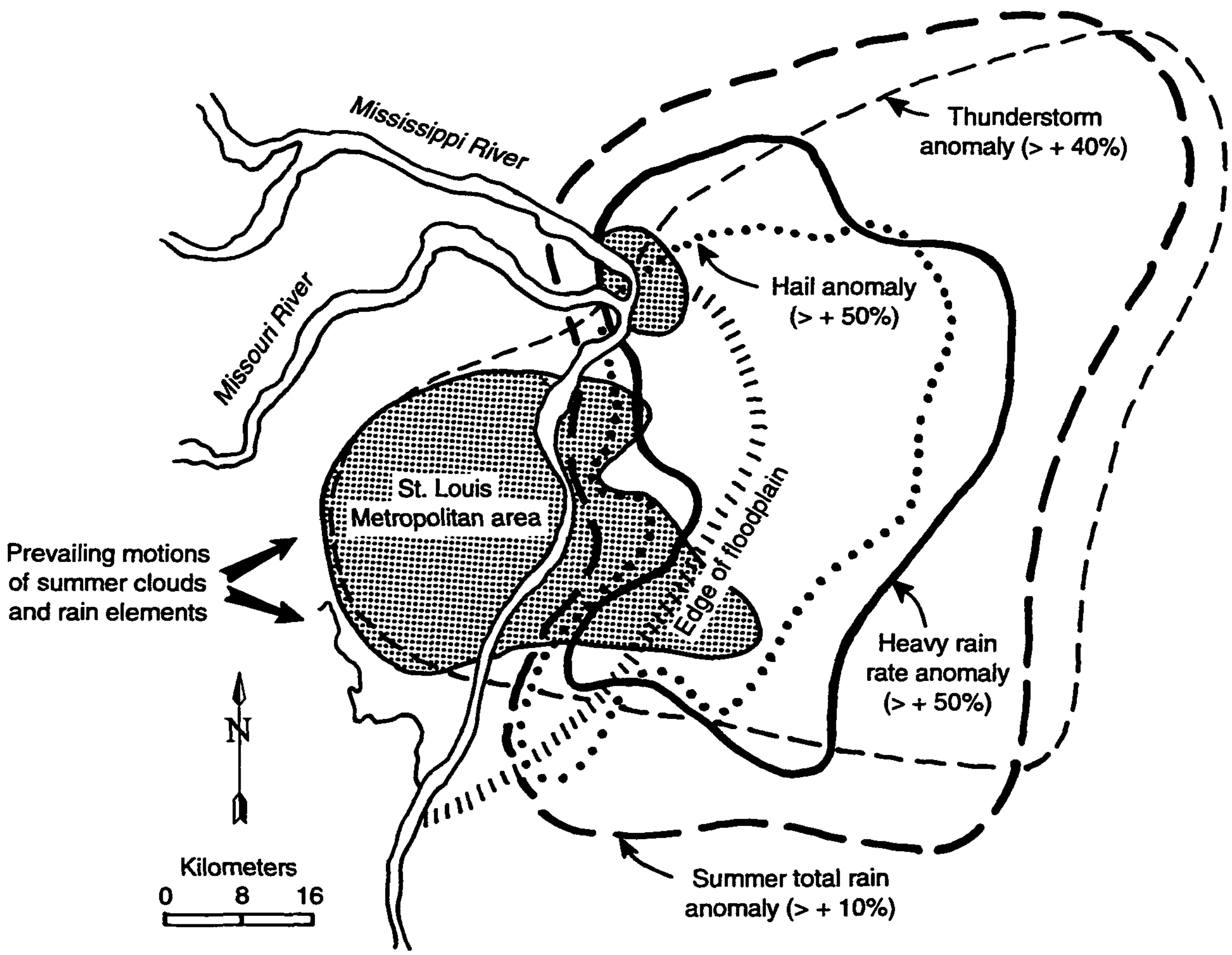


Figure 1. Climatological anomalies in summer (June-August) rainfall and storm activity caused by various influences of St. Louis on the atmosphere (Changnon, 1981b)

THE ILLINOIS CLIMATE

Factors Affecting the Climate of Illinois

Several factors control the climate of Illinois: 1) output of the sun, 2) shape of the earth and its distance from the sun, 3) location of Illinois with respect to its latitude and to major sources of moisture (oceans), 4) composition of the earth's atmosphere, and 5) thermal characteristics of the earth's surface. The first two characteristics change over time, but only on scales exceeding thousands of years. The locations of major moisture sources do not change. The thermal characteristics of the earth's surface (emissivity, albedo, and heat content) change as a function of vegetative cover and time of year. Human activity has changed vegetation, and thus has caused some change in climate over the last 200 years. The constituents of the earth's atmosphere including water vapor and various chemicals in the form of gases play a role in the radiation balance of the earth, and these change over time scales of years.

Historical Shifts in the Climate of Dlinois

Instrumental observations of temperature and precipitation are available for more than 100 sites in Illinois since the turn of the century. About 40 of those sites began in the 1880s, a few began as early as I860, and one (Chicago) began in 1830. From these data, we know that Illinois' mean temperature warmed by about four degrees fahrenheit from the mid-1800s to 1930, then cooled by about two degrees (F) until 1980, after which it again appears to be warming. During those same years, statewide mean precipitation was essentially constant, but exhibited great year-to-year variation. The last few decades of the 19th century were the end of the so-called neo-Boreal climate episode, from the mid-1500s till about 1880 when the Northern Hemisphere was cooler by a few degrees than it is today.

Just as weather may differ dramatically from year to year, or differ from "normal" conditions, the climate conditions over several years such as a decade may differ from a longer term 40- or 100-year average. When do such changes from the long-term average become "climate change" as opposed to "climate variability"? There is no concrete answer. "Variability" represents a "temporary" condition that eventually returns to the original condition, whereas "change" represents a rather definite prolonged discontinuity from the past, to a new episode where the averages and variances of various climate conditions are distinctly different from previous conditions, and are not expected to revert. In many ways, the difference between "variability" and "change" depends on the purpose and time period for which the question is asked.

To reconstruct the climate prior to the period for which records are available, proxy environmental information for Illinois and much of North America is required. Fortunately, several pollen analyses completed from data within the state yield an integrated environmental history going back several thousand years. King (1981) analyzed three pollen cores from northern Illinois that provide a vegetation history going back to about 14,000 years before the present (BP). These data show that a boreal forest (black and white spruce) dominated as far south as Livingston County until about 13,000 BP and still remained in Lake County at 11,000 BP. Thus it can be inferred that temperatures in Illinois were much cooler than those of today by 10 to 15 degrees fahrenheit. Again, by inference, precipitation in Illinois was less than today, probably by some 20 to 30 percent.

As the climate warmed, the boreal forest withdrew northward out of Illinois. A grassland community then migrated into the state, establishing a condition that has generally persisted to the present, but with significant variations lasting decades and centuries within that 10,000-year period.

For example, worldwide temperatures, as well as those in Illinois, warmed, reaching a maximum from about 8,500 to 5,000 years BP, amounting to 5 to 10 degrees fahrenheit warmer than today's climate in Illinois. Although there were significant climate fluctuations, with attendant shifting influences on plants and animals present in Illinois during the last 10,000 years, those from late-glacial time (prior to 11,000 BP), and those from about 8,500 to 5,000 BP, represent the coldest and warmest episodes during the last 15,000 years, respectively.

THE GREENHOUSE EFFECT

Greenhouse Effect Essential to Life on Earth

The greenhouse effect refers to the impact that atmospheric water vapor, carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons (CFCs) exert on the earth's radiation budget. In the absence of these greenhouse gases, sunlight (short-wave radiation) and energy radiated from the earth out to space (long-wave radiation) freely pass through the atmosphere with virtually no absorption en route. Greenhouse gases, although transparent to incoming short-wave radiation, are relatively opaque to the outgoing longer wave radiation. The result is that sunlight reaches the earth's surface unimpeded, but that the radiation emanating from the earth is, in part, absorbed by the greenhouse gases in the atmosphere. This radiation is partially reradiated back to earth, thus making the earth's surface 60 degrees fahrenheit warmer than an equilibrium temperature would be in the absence of these gases! Without the greenhouse effect to moderate the surface temperature, plants and animals could not survive on earth. All other things being constant, as the concentration of greenhouse gases increases, so too does the magnitude of the related warming.

Alterations to the Greenhouse Effect and Climate Implications

Atmospheric CO_2 has increased 0.5 percent per year during the last 30 years and 20 percent since the industrial revolution. Although the atmospheric concentration of CO_2 is still very small, it is sufficient to account for some warming of the earth relative to a radiation-balanced temperature alone. Figure 2 shows the increase in CO_2 concentration from 1745 to 1960, as determined from samples of air trapped in ice cores, and from direct measurements from 1958 to the present made at Mauna Loa Observatory in Hawaii. This remote site, far from industrial sources, is thought to be a good measure of global concentrations.

The concentration of atmospheric $CO_2$is expected to continue to increase, at a faster rate than at present, due to an increasing world population, continued economic development, and an ever-increasing global thirst for energy. This condition alone absolutely requires that the earth become warmer. However, although CO_2 consistently increased in concentration during the last century, this trend was not mirrored by mean temperatures for Illinois, the Northern Hemisphere, and the world. Temperatures warmed from 1880 to about 1930 and then declined until 1980, the very period when CO_2 production was increasing at its fastest rate. There is no doubt that the increasing CO_2 forced warmer temperatures, but several decades of cooling during the mid-twentieth century indicate that some other force or forces acted to cool the earth by an even greater amount. This cooling force or forces could result from 1) changed vegetation over the earth, 2) increased concentration of atmospheric aerosols, 3) altered ocean circulation and sea surface temperature patterns, 4) changed solar output, and/or 5) increased cloudiness. Vegetation cover has changed from forest to cropland in many low- and mid-latitude land masses over the last century. This change increases the earth's albedo, reflecting more sunlight away from the earth and having a cooling influence. Although

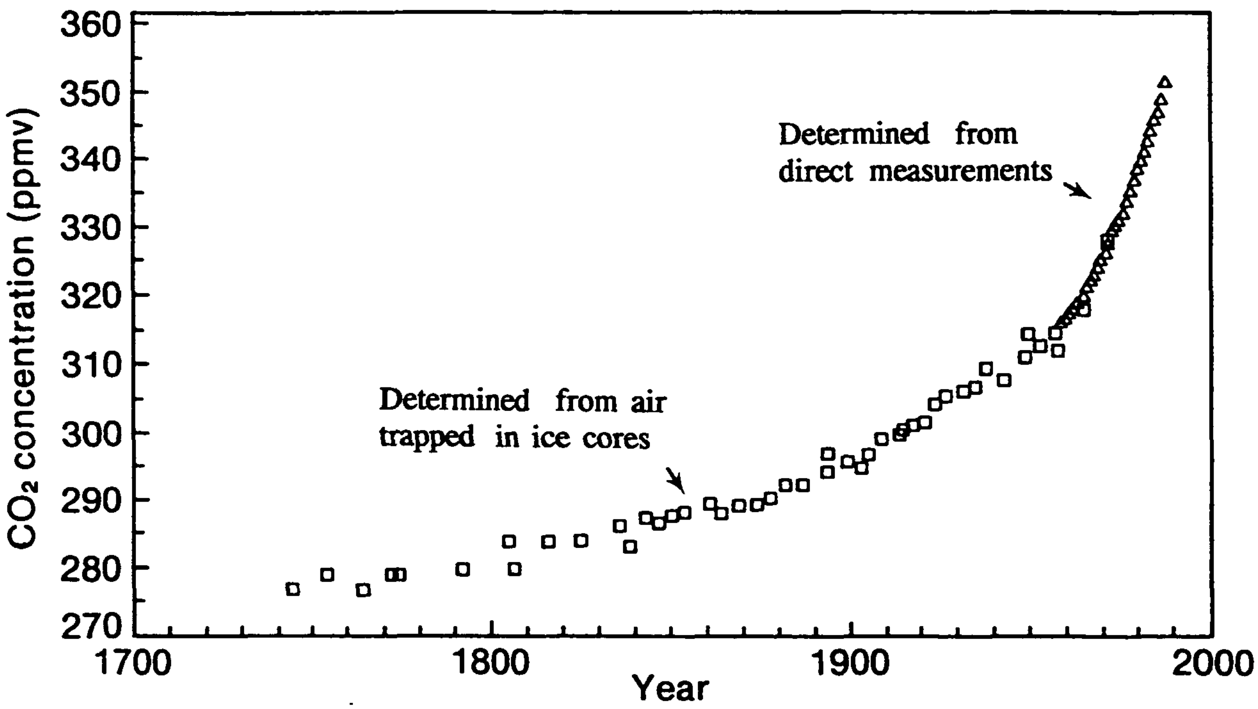


Figure 2. Atmospheric CO increase in the past 250 years

observations are incomplete spatially and temporally, atmospheric aerosol concentration has been increasing. Davitaia (1965) showed that (atmospheric) aerosols trapped in ice from the Caucasus Mountains of the Soviet Union increased from about 10 milligrams per liter (mg/1) from 1880 to about 1930, to about 220 mg/l by 1960. This rapid increase coincides with those decades of worldwide cooling subsequent to 1930. Wendland and Bryson (1970) suggested that cooling due to this increase in aerosol concentration overshadowed the warming due to CO_2. Balling (1991), Michaels and Stooksbury (1992), and others indicate a strong belief in the cooling effect of aerosols. Changnon (1985) showed that cloud cover has been increasing in Illinois since 1930, and part of this increase is due to clouds produced by jet aircraft contrails (Changnon, 1981a).

Global CO_2 has been increasing notably since the Industrial Age began in the nineteenth century. One reason for concern over the increase in atmospheric CO_2 due to human activities is based on the reconstruction of the CO_2 and temperature conditions over the past 160,000 years using deep ice cores (figure 3). Gas analyzed from Vostok ice cores reveals a direct correlation between gas concentrations and temperatures over this time period; that is, when the CO_2 has been higher, temperatures have been higher. What cannot be determined, however, is the cause-effect relationship. When temperatures increase, is more CO_2 released into the atmosphere or do the oceans absorb less CO_2? When CO_2 increases, does it cause the temperature to increase? In addition, as temperatures change, CO_2 is released into the atmosphere or absorbed by the oceans, but this occurs many decades after the temperature change.

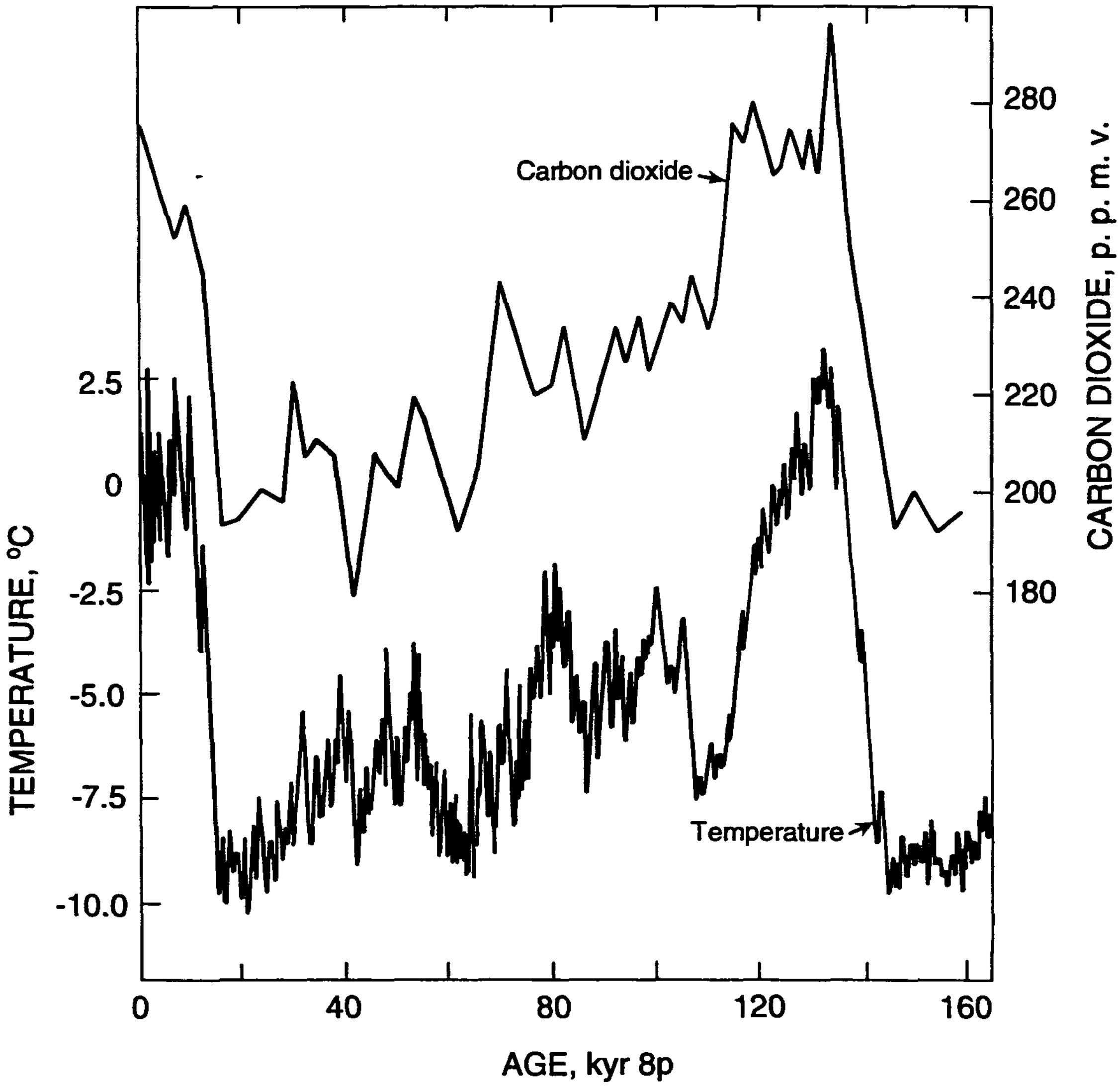


Figure 3. CO. levels and temperatures from the present back 160,000 years, as determined from Vostok 5 ice core (Houghton and Woodwell, 1989)

GENERAL CIRCULATION MODELS

The Models

General circulation models (GCMs) are complex computer programs designed to analyze atmospheric behavior. They have been used to predict, given initial conditions, future environmental conditions for the earth's surface and at several levels in the atmosphere. The models are based on laws of physics and a substantial number of statistical relationships between temperature, vertical motion, probability of precipitation, and so forth. The GCMs require large computers and many hours to generate stable "climatic" environmental parameters.

Each model begins with an earth at uniform temperature, and present atmospheric conditions, after which a 24-hour solar heating-cooling cycle is initiated. Temperature, humidity, and other conditions respond to that forced heating-cooling cycle and typically reach "equilibrium values" modeled several decades in the future. The final output is generally in the form of mean monthly temperature and precipitation values for each grid point. The effect of altered gaseous constituents can be simulated in the models to estimate changes produced in surface temperature and precipitation.

Climatic values were derived for the Illinois area from four GCMs: the Princeton University Geophysical Fluid Dynamics (GFDL) model, the Goddard Institute for Space Studies (GISS) model, the Oregon State University (OSU) model, and the United Kingdom Meteorological Office (UKMO) model. These multi-layered (vertically) gridded databases predict future climate at grid intersections around the globe.

Due to computer memory limitations, GCMs use very wide grid spacing equivalent to several degrees latitude and longitude (see table 2), and values are projected for each grid square. Such grid spacing means that grid points are hundreds of miles apart. This space limitation does not permit the models to recognize small cyclones, hurricanes, squall lines, and individual thunderstorms, nor to describe the climate variations across areas the size of Illinois.

Table 2. Latitude and Longitude Spacing (Degrees) of the Gridded Data Available to This Study for Climatology and the Four GCMs.

GCM	Latitude	Longitude
GFDL	4.4	7.5
GISS	7.8	10.0
OSU	4.0	5.0
UKMO	5.0	7.5

Differences between the models include the individual means of parameterizing the variables, and the intervals used for each prediction step among other factors. The greatest differences are likely those caused by the various means of parameterization. As a result, predicted temperature and precipitation values at similar grid points can vary significantly between models.

The Scientific Debate over GCM Predictions of Global Warming.

There has been intense scientific scrutiny of GCM assumptions concerning doubling of CO_2, and the inability of models to exactly replicate today's weather conditions. Predictably, scientific debate has developed over the accuracy of GCM predictions of global wanning. However, most atmospheric scientists who have been extensively involved in climate change research have accepted the general conclusions concerning warming (Slade, 1990). The American Meteorological Society (1991) issued a policy statement on the issue of global climate change, from which excerpts are reproduced below.

POLICY STATEMENT

American Meteorological Society
(1991)

- Human changes to atmospheric composition of greenhouse gases are unmistakable.
- The influence of greenhouse gases on the earth's energy balance is not controversial.
    - These gases will lead to warming if no other factors counter their influence.
    - However, magnitude and timing of any climate change is controversial.

Under the Intergovernmental Panel on Climate Change, leading atmospheric scientists from around the world have been convened to assess GCM data and findings. In 1992, this panel of scientists under the leadership of the World Meteorological Organization, issued a statement concerning the status of global climate change. A summary of their 1992 statement follows.

- Emissions resulting from human activities are substantially increasing atmospheric concentrations of the greenhouse gases: carbon dioxide, methane, chlorofluorocarbons, and nitrous oxide.
- The evidence from modeling studies, observations, and sensitivity analyses indicates that the sensitivity of global mean surface temperature to doubling CO_2 is unlikely to lie outside the range of l.5°C (2.7°F) to 4.5°C (8.1°F).
- There are many uncertainties in our predictions, particularly with regard to the timing, magnitude, and regional patterns of climate change.
- Global mean surface air temperature has increased by 0.3 ° to 0.6°C over the last 100 years.
- Although the magnitude of this wanning is broadly consistent with GCM predictions, it is also of the same magnitude as natural climate variability. Thus the observed increase could be

largely due to this natural variability; alternatively, this variability and other human factors could have offset a still larger human-induced greenhouse warming.

- The unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more.
- The cooling effect of aerosols resulting from sulphur emissions may have offset a significant part of the greenhouse warming in the Northern Hemisphere (NH) during the past several decades. Although this phenomenon was recognized in the 1990 report, some progress has been made in quantifying its effects.

Many scientists heavily involved in global modeling and study of the issue firmly believe that global warming is inevitable. They have provided strong arguments for their findings (Rind, 1989; Schneider, 1990; Kellogg, 1992).

A primary issue among those scientists who have questioned the validity of GCMs and their estimations of global warming is whether temperature behavior during the past 100 years (generally increasing from the mid-1800s to about 1930, with cooling thereafter) reflects the effects of CO_2. Those scientists supportive of a warming theory essentially claim that warmer temperatures during the 1980s are consistent with an influence due to the increases in CO, (Rind, 1989).

However, other scientists have challenged this conclusion. They suggest that temperature behavior during the past 100 years has been well within normal variations of past fluctuations (Michaels and Stooksbury, 1992), or that other factors have been significantly involved. For example, additional sulfate aerosols would act to cool the climate. The warming of temperatures in the higher latitudes has not matched the model-derived predictions of greatest warming. Further, much of the actual warming has been in the form of nocturnal, low temperatures in excess of what

GCMs project should occur under enhanced greenhouse effects. In attempts to clarify the historical record, other scientists have argued that the global temperature behavior of the past 100 years is a mixture of natural and by man-made factors that may be counteracting each other. For example, CO_2 tends to increase temperatures, and increased sulfate aerosols tend to decrease temperatures (Duffy, 1993). Kerr (1991) proposed another theory about the general warming trend during the past 100 years, which claims that it is related to shifts in solar activity and our lack of understanding of how effectively solar activity can alter surface temperatures of the earth. Balling (1991) claimed that the projected warming values for the next century were double the amount that would actually occur.

Kunkel et al. (1993a) assessed upper air flow patterns associated with heavy precipitation events in the Midwest and compared the observed conditions with those predicted by GCMs. They found that GCMs generally failed to reproduce the frequency of occurrence of flood-producing weather events under conditions in which such events have actually occurred during the past 80 years. This raises concern about the accuracy of those GCMs operated for a doubling of CO_2 in estimating heavy precipitation events, and the possible impacts on flooding frequency and severity.

Along with this scientific debate over GCMs and the accuracy of their predictions of global warming, there are also some scientific and ethical questions. Has global warming been "promoted" as a theme to effect environmental policy (Brookes, 1989) and as a "cause" to increase scientific funding (Eagleson, 1991)?

Concerns raised by the global warming theorists have occasionally tended to lean towards a gloom-and-doom global outcome (Houghton and Woodwell, 1989; Kellogg, 1992; Schneider, 1990). Ausubel (1991a) challenges the seriousness of the effects of climate change and argues that in many ways society will be able to adapt to the types of changes being predicted. He further illustrates that there will be a mixture of "winners and losers" under a changed climate, and that the areas of serious concern about climate change are water and biological resources unable to adapt to change (Ausubel, 1991b). Balling (1991) argues that the warming would occur mainly in the winter and would thus be largely beneficial.

The many warm years in the 1981-1991 period prompted some popular support for the belief that global wanning had begun. Ropelewski et al. (1993) claim that these temperatures were well within the limits of past climate variability.

It is important to realize that until a detectable change in climate has been convincingly demonstrated, the scientific uncertainty and debate surrounding the topic will continue (Changnon, 1992c). This is to be expected. Nevertheless, this does not remove the need to consider the global warming issue and related policies, whether it be to sustain the scientific research to plan for climate change, or to act to mitigate climate change. The climate of the next 10 to 50 years in the United States and elsewhere will be different than it has been for the past 50 years, regardless of human effects. This is not subject to conjecture. Our climate has never been stationary (Changnon, 1977).

FUTURE CLIMATE SCENARIOS

The outputs of the various GCMs have been used to generate potential future climatic conditions primarily as a basis for studies of the possible range of effects of a changed climate. This document presents the outputs of four of the GCMs that have been used in Illinois in Intergovernmental Panel on Climate Change studies whose focus is the possible effects of climate change. Their inclusion does not favor one GCM over another, nor does it deny the assumptions involved in each GCM. The values are presented as only four of many potential future outcomes.

Climate Scenarios from GCMs.

To evaluate climates resulting from a doubling of atmospheric CO_2 concentrations over those of 1950, the differences between conditions were modeled using an atmosphere having 2 X CO_2 and the "current" atmosphere. Table 3 presents an atmosphere having the predicted monthly temperature and precipitation values based on 2 X CO_2 which are expressed in relation to the modeled values for current conditions. The values presented are based on the modeled values for the grid points in Illinois or closest to it. First, note that three of the four models predict annual warming of about eight or more degrees (F) above the temperatures modeled for the current time. The Intergovernmental Panel on Climate Change's (1992) range of possible global average temperature changes is 2.7°F to 8.1 °F (1.5°C to 4.5°C), and thus the estimated change in Illinois and the Midwest is greater than the global average highest value. This reveals that the models expect the Illinois area to become one of the warmer locations on earth. These same three models also suggest greater warming during the winter (+10.6°F), as opposed to +8°F for the summer months. Although the UKMO model suggests an annual increase (+13.7°F), it is less clear whether the warming will be greater in winter than the summer.

On a monthly basis, the models also suggest quite different changes to precipitation from those modeled without doubling the CO_2 (table 3). The OSU model suggests a drier spring than today's but wetter conditions during the remaining months. The GISS, GFDL, and UKMO models all suggest drier autumns. The GFDL model predicts substantially less precipitation from June through November. In spite of these differences between models, they all predict a future that is "warmer than today." The averages of the four modeled departures show a warmer, wetter winter

(December-March), and a hotter, slightly drier summer (June-September). Although the three models predict slightly greater precipitation than today's during most months, it is distributed differently throughout the year. Even with precipitation somewhat greater than current averages in three of the four models, the potential evaporation would be expected to offset the rain increase due to the higher temperatures, causing lower soil moisture during the growing season. Substantial differences between the monthly values of the four models indicate substantially different outcomes or effects, both in the natural ecosystem and in the state's economy. For example, the GFDL model results in a hot and dry summer, whereas the GISS model results in a hot and wetter summer than today's. These differences would result in substantial differences in crop yields (see table 8).

Table 3. Projected Changes in Mean Monthly Temperature and Precipitation for Illinois under 2 X CO_2 Atmospheric Concentrations Based on Four GCMs.

	OSU		GISS		GFDL		UKMO		Averages	
	Temp °F	Prec %nrm	Temp °F	Prec %nrm	Temp °F	Prec %nrm	Temp °F	Prec %nrm	Temp °F	Prec %nrm
Jan	+10.1	108	+11.2	117	+9.2	146	+16.7	122	+11.9	123
Feb	+6.5	127	+9.9	103	+11.0	128	+15.3	121	+10.6	119
Mar	+7.6	112	+9.4	128	+12.2	106	+13.5	129	+10.6	118
Apr	+4.9	86	+9.2	103	+6.5	100	+13.5	116	+8.5	101
May	+6.1	82	+4.7	112	+6.5	100	+11.2	123	+7.2	104
Jun	+7.7	94	+6.7	108	+7.2	72	+10.3	117	+8.1	98
Jul	+5.8	108	+4.0	no	+8.5	62	+112	101	+7.4	95
Aug	+7.0	107	+6.8	98	+4.9	96	+157	95	+8.6	99
Sep	+6.5	120	+12.6	70	+9.5	74	+13.5	99	+10.6	91
Oct	+5.8	120	+6.7	88	+11.0	93	+11.5	88	+8.8	97
Nov	+3.6	95	+11.0	99	+9.5	82	+14.0	109	+9.5	96
Dec	+5.8	101	+10.6	124	+5.2	108	+16.7	126	+9.5	116
Ann	+6.5	105	+8.6	105	+8.5	92	+13.7	112	+9.4	105

Note: OSU = Oregon State model; GISS = Goddard model; GFDL = Princeton model; UKMO = United Kingdom model. (% nrm = percent normal)

Table 4 presents some predicted climate changes specific to Illinois' growing season based on the GFDL model. Note the substantial increase in the average number of days per year with temperatures greater than 90°F, the reduction in the number of days with temperatures less than 32°F, and the 53-day increase in the length of the growing season.

It is generally accepted that the GCMs have serious limitations for predicting the future. In fact, some climate modelers have argued against the use of their models to predict the future climate. But even with their existing limitations, the GCMs all generate a wanner climate for Illinois under a global doubling of CO_2. The expected range of global warming varies from 1.5°C to 4.5°C (IPCC, 1992).

Table 4. Likely Changes in Central Illinois' Thermal Climate under Twice the Current Carbon Dioxide Levels, as Predicted by the GFDL Moc el.

Condition	Current	With 2 x CO_2	Change
Highest max temperature	103	109	+6
Lowest min temperature	-25	-15	+10
# days/year T >90°F	21	75	+54
# days/year T<32°F	43	10	-33
# days/year T<32°F	125	60	-65
# days/year T<0°F	11	0	-11
Last spring frost	mid April	mid-arch	1 month
Earliest last spring frost	March (1st week)	February (3rd week)	5 weeks
Latest last spring frost	May (1st week)	April (1st week)	1 month
First fall frost (avg)	mid-October	mid-November	1 month
Earliest fall frost	September (last week)	October (3rd week)	3 weeks
Latest fall frost	November (1st week)	December (1st week)	1 month
Growing Season Length	188 days	241 days	+53 days

Climate Scenarios from Analogs

Certain studies attempting to estimate the range of future weather conditions and effects of altered climate in Illinois have employed scenarios developed by using historical "analogs." Changnon (1991a) explored the various means of developing such historical analogs and assessed their uses. Most historical analogs used for research purposes in Illinois research have either been based on runs of extreme conditions of the past, such as the 1930s (Changnon and Huff, 1991), or based on the selection of extreme years from the historical record. In a study of the effects of potential extreme conditions on the hydrology of the Great Lakes basin, Quinn and Changnon (1989) selected the 12 wettest and 12 driest years from the 140-year historical record for the Great Lakes basin to form consecutive periods of potential extreme conditions. These data were input to hydrologic models of the Great Lakes basin to estimate their effects on net basin water supplies and lake levels, and as rain values for the Lake Levels Reference Study (International Joint Commission, 1989).

Some research focusing on Illinois and based on analogs has attempted to ascertain the incidence of certain weather features under potentially altered climate conditions. For example, in a study of Illinois cloud characteristics of the past, Czys et al. (1993) measured coalescence activity in summer rain clouds. Their results indicate that during warmer and drier periods, atmospheric conditions did not favor the development of as many clouds producing rain during summer, but the drier conditions favored rain production by coalescence processes. The net effect would be reduced precipitation and less cloud cover.

The occurrence of heavy rainfall events from past wet and dry periods was investigated to determine the potential effects of altered climate on design rainfall frequencies (Changnon and Huff, 1991). They found that the drier periods of the past, such as the 1930s and 1950s, had experienced many fewer heavier rainfall events in the 2- to 10-year recurrence interval range than other wetter periods.

Other studies examined the historical behavior of thunderstorms and events produced by thunderstorms to obtain predictions of future behavior. Gabriel and Changnon (1989) analyzed historical records of thunderstorm activity and concluded that the drier periods in the Midwest, such as the 1930s, actually experienced a greater frequency of storm days than did wetter periods. Studies of hailstorm frequency in Illinois (Changnon, 1984) revealed that previous warmer and drier periods generally had less intense but more frequent hailstorms. Changnon and Changnon (1992) analyzed the incidence of catastrophic storms in the Midwest from 1949 to 1990. This study revealed that the Midwest experienced more catastrophic storms during the warmer 1950s and 1980s than during the cooler and wetter 1960s and 1970s. Kunkel et al. (1993b) analyzed the temporal characteristics of heavy precipitation events in the Midwest. Their findings indicated fewer flood-producing precipitation events during the drier periods of the past 70 years.

All these assessments of severe weather indicate a high frequency of thunderstorms, hail, and catastrophic storms during warmer periods than during wetter periods. However, the amount of rain and incidence of heavy rain-producing events actually decreased during the warmer, drier periods. This outcome suggests that warm periods, as predicted by the GCMs, would lead to more frequent convective storms in Illinois, but that the storms in general would be less intense and less likely to produce heavy rainfall events.

POTENTIAL EFFECTS OF GLOBAL WARMING IN ILLINOIS

Water Resources

Several studies have attempted to measure the possible influences of altered climate conditions on the quantity and quality of water resources, (Changnon, 1988a). A national study of the potential effects of climate change on water resources pointed to a series of potential severe effects (AAAS, 1989). In the Midwest, and thus in Illinois, under the suspected warmer-drier climate, these effects included reduced streamflows, lower lake levels, and reduced ice coverage on the rivers and the Great Lakes. This national study concluded that the potential severity of the water resource problems would lead to major controversies and, in turn, necessitate alterations in water management practices and water laws. Ausubel (1991b), has challenged the concept of disaster from climate change but admits that one of the more serious concerns would be its effects on water resources.

Changnon (1992a) presented an overview of the potential effects of climate change on water resources in Illinois. Increased demand and decreased supplies would occur with a warmer and effectively drier future climate resulting from greater evaporation. Our large urban water-supply systems are becoming obsolete and need to be replaced, which puts additional stress on our water supplies.

Changnon (1987d) analyzed historical droughts in Illinois because droughts have been considered as possible "analogs" of future drier climate conditions. Table 5 shows the effect of historical three-year dry periods on the flow of the Sangamon River, and modest decreases of 7 to 11 percent were related to major decreases in streamflow, ranging from 43 to 54 percent.

Knapp and Durgunoglu (1993) used ten climate scenarios of changed temperature and precipitation in a four-dimensional model of an Illinois basin. They found that Illinois water-supply systems were highly sensitive to small changes in temperature and rainfall. For example, a 5°F increase in temperature produced a 40 percent decrease in reservoir yield. Their results indicated that many water-supply reservoirs in Illinois would be inadequate with only moderate changes in climate.

Table 5. Relationship of Below Normal Precipitation and Streamflow on the Sangamon River Basin, 1921-1990 for Three-Year Periods.

	Percent departure below normal	
Ranking	**Precipitation (percent)**	**Streamflow (percent)**
5th driest	7	43
4th driest	9	45
3rd driest	11	54
2nd driest	20	79
driest	24	83

Changnon et al. (1993b) analyzed historical periods of flooding in Illinois and the surrounding states. Drier historical regimes were associated with 35 to 50 percent reductions in the magnitude and frequency of annual floods. Changnon (1983) found that floods in Illinois were closely related to the incidence of rains of 2 inches or more, and that these rain events were most frequent during wet decades. After analyzing the effects of historical climate variations on Illinois River flows and floods, Singh and Ramamurthy (1990) concluded that only moderate shifts in rainfall would create major changes in river flows and in flooding frequencies. Drier conditions in Illinois would mean fewer floods.

Huff (1992) analyzed the relationship between surface water temperatures in Illinois rivers and air temperatures, and found a close relationship. During climate warming increased river water temperatures could conceivably produce water quality problems as well as cooling water problems for on-river users.

In assessing how future precipitation changes could affect Illinois, Changnon and Easterling (1989) found if instructive to have experience with past previous departures, as measured against drought severity in Illinois. In all parts of Illinois, precipitation departures of 10 percent for two years produced "moderately severe" droughts. Table 6 shows that 2-year precipitation values, which are 18 to 30 percent below average, produce severe drought conditions in Illinois. "Severe" is defined as those situations which required major adjustments such as sizable capital outlays for new water facilities, including new reservoirs, dam spillways, and permanent pipelines for water. Such findings make it possible to interpret the potential range of impacts and adjustments as a result of by precipitation decreases of varying amounts.

Table 6. Precipitation Departures (in Percentages), Causing Moderate and Severe Droughts of 2-Year Duration.

Drought	North	Central	South
Moderate	≤90	≤90	≤88
Severe	≤82	≤75	≤70

Another climate change study related to water resources impacts on Lake Michigan. Hartmann (1990) entered data from utilized three climate scenarios based on three GCMs in a Great Lakes basin hydrologic model to estimate effects on the average levels of the Great Lakes. This study generated levels for Lake Michigan that were 2.8, 4.1, and 8.3 feet lower than the average level. These levels were used to estimate potential effects on the Chicago shoreline (Changnon et al., 1989). The climate scenario in which the average lake level decreases by 2.8 feet would necessitate adjustments totaling $100 million (1988 dollars). Table 7 summarizes the economic effects to modify inflow systems, outflow systems, and harbors for the climate scenario in which the average lake level drops 4.1 and 8.3 feet (Changnon, 1993a). These greater decreases have serious economic consequences, particularly as they relate to costs to sustain the diversion of waters from Lake Michigan into the Chicago River and canal system and then down the Illinois River. The costs to modify the diversion system vary widely but are large, (up to $25 billion for the 8.3-foot drop.)

Although there have been several probing studies, there are major topics relevant to climate change and its effects on Illinois water resources about which little or no information is available (Changnon, 1987c). One such topic is the potential effects of climate chnage on the quality of Illinois rivers, lakes, and wetlands. For example, a major decrease in streamflow of the Illinois River system could have extremely serious effects on the level of dissolved oxygen and the river's ability to assimilate wastes. And, little is known about the variety of potential effects on the diversion system at Chicago, an extremely critical issue for that city and the Illinois River basin. And virtually nothing is known about the effects of climate change on ground-water supplies or their quality.

Table 7. Estimated Costs to Adjust for Major Reductions in Average Level of Lake Michigan.

Adjustment	4.1 feet lower[b]	8.3 feet lower[b]
Recreational harbors		
Dredging	30-50	75-125
Sheeting/bulkheads	15-25	35-50
Slips/docks	20-30	40-60
Commercial harbors		
Dredging	110-150	250-350
Sheeting/bulkheads	38-40	38-40
Slips/docks	40-45	90-100
Water supply sources		
Extending urban intakes	16-20	24-32
Additional intakes	20-25	40-48
Beaches		
Relocate	5-10	5-10
Outfall for a stormwater		
Extend and modify	4-6	8-12
Subtotal	$298 to $401 million	$605 to $827 million
Modify urban diversion system	$1.5 to $10 billion	$5 to $25 billion

NOTES:
[a]Costs (unless marked) are in millions of 1988 dollars.
[b]Indicated depths below the 1951-1980 average level.
[c]Costs are in billions of 1988 dollars.

Effects on Agriculture in Elinois

Agricultural production is recognized as one of the more weather-sensitive activities in Illinois. As one of the nation's leading states in corn and soybean production, a shift in climate raises great concerns. Investigations of possible effects of climate change on agriculture have largely focused on the effects on corn and soybean yields, and some of the economic impacts that might occur (Ritchie et al., 1989; Onal, 1992).

Changnon (1992b) assessed the issue of climate change and its effects on Midwestern agriculture. Previous farm practices have reduced the sensitivity to weather, during planting and harvesting, but Illinois' high-production grain agriculture is still susceptible to severe losses during summer droughts such as those during 1980, 1983, 1988, and 1991. Figure 4 illustrates how corn and soybean yields in Illinois varied according to the summer mean temperatures over the past 14 years, and there is a strong relationship between summer temperatures and the production of these two crops. The figure also indicates summer mean temperatures estimated by three GCM scenarios and the actual mean temperatures during the 1930s. The much higher temperatures with the models suggest a considerable reduction in yields, although the amount of precipitation is also important. Conditions that lead to summer warming clearly would be detrimental to crop production, particularly if rainfall was unchanged or lower. The question is, how much lower would yields fall?

Ritchie et al. (1989) used the climate values of two GCMs that predicted monthly weather conditions for several locations in and around Illinois to derive a series of estimates of the effects of these changed growing season conditions on corn and soybean production. The study included conditions acting to decrease yields (more hot, dry weather) and conditions acting to increase yields (plant enrichment due to added CO_2) in the atmosphere. The assessment of the effects of these counteracting forces is shown in table 8 for northern, central, and southern Illinois using two models for corn and two models for soybeans. The table indicates a wide range of outcomes varying from rather sizable com yield decreases (GFDL model), to sizable increases in corn yields (GISS) model.

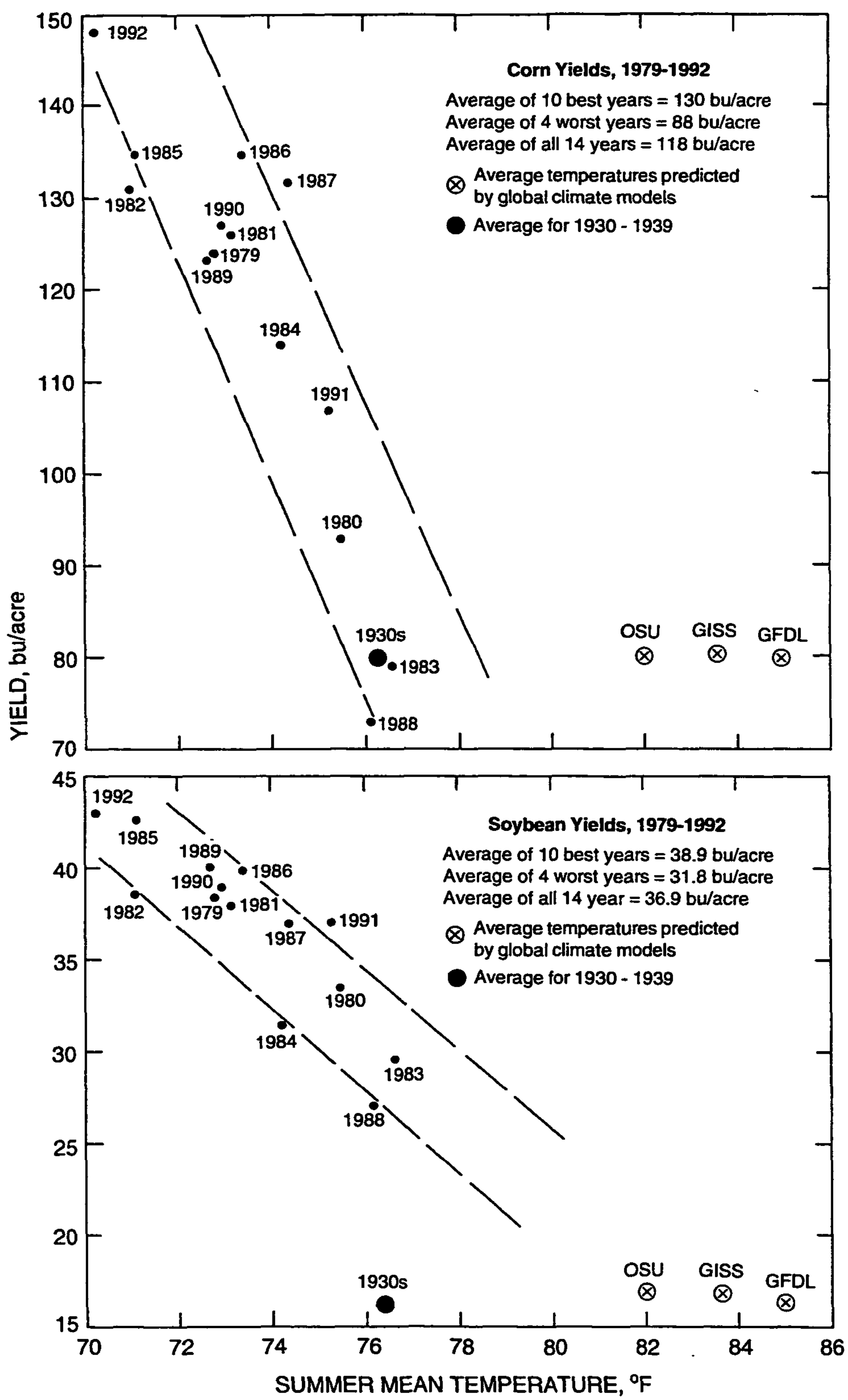


Figure 4. Relationship of recent (1979-1992) summer crop yields and mean temperatures in Illinois

The models also produce sizable differences for soybean yields. These "sensitivity studies" reveal a range of what "could happen, not what will happen."

Economists have used these yield outcomes to assess the effects of these yield changes on crops grown in Illinois, on farm income, and on the general economic picture (Onal and Fang, 1991). Their studies indicate an average shift of 3 percent decrease in corn planted and conversion to wheat and soybeans. Shifts in wheat acreages were +33 percent (GISS model) and +85 percent (GFDL model), and for soybeans the acreage shifts were +3 percent (GISS) and +36 percent (GFDL). An economic analysis (Onal, 1992) concludes that the GFDL climate scenario leads to lower yields and higher prices for wheat, corn, and soybeans, and the GISS scenario results in lower prices for all crops. The results indicate that none of the climate scenarios lead to a severe problem for sustaining Illinois agriculture, although shifts would occupy in quantity of crops grown and prices. Thus, depending upon the climate scenarios used, Illinois agriculture could win or lose, depending upon what kind of climate change occurs in Illinois and other grain-producing regions.

Table 8. Percent Change in Crop Yields Based on Two Climate Models.

Model	**Northern Illinois**	**Central Illinois**	**Southern niinois**
Corn GFDL model	-30	**-20**	**-15**
Corn GISS model	+10	+40	+60
Soybeans GFDL model	-5	-10	+10
Soybeans GISS model	+100	+80	+50

(After Ritchie et al., 1989)

There have been no investigations of potential agricultural impacts of climate change on other crops such as wheat, on livestock production, and on agribusinesses in Illinois.

Other Potential Physical Effects and Socioeconomic Impacts of Climate Change in Illinois

Beyond the aforementioned studies of water resources and agriculture, little is known about the range of effects that different climate conditions could have on the environment, natural resources, or on other socioeconomic sectors of Illinois. Limited studies of the effects of urban-produced increases in summer rainfall and storminess in the area east of St. Louis revealed an increase in traffic accidents and power outages, and a decrease in recreational events as shown in figure 5 (Changnon, 1981b). Subsequent studies of Chicago found that the urban area has enhanced the amount of rainfall also found corresponding increases in traffic accidents, delays, and power outages when compared to unaffected rural areas west of the metropolitan area (Bertness, 1980).

Angel et al. (1991) established that little was known about the effects of climate on various Illinois trees and they concluded that no reliable estimate of the effects of changed climates on Illinois forests could be made. However, Schwartz (1992) stated that Illinois tree species would move northward 100 miles with each 1°C increase in average temperature, and it would take various tree species 100 years to shift 10 to 20 miles. Hence, he claimed that a rapid climate shift, as the GCMs predict, would lead to a loss of tree species and a decrease in forest diversity in Illinois.

The general lack of long-term historical data on the biota of Illinois makes it difficult to the comparative studies of biological fluctuations under fluctuating climate conditions. However, there are opportunities for studies yet to be initiated that relate historical climate fluctuations to certain plant species in Illinois.

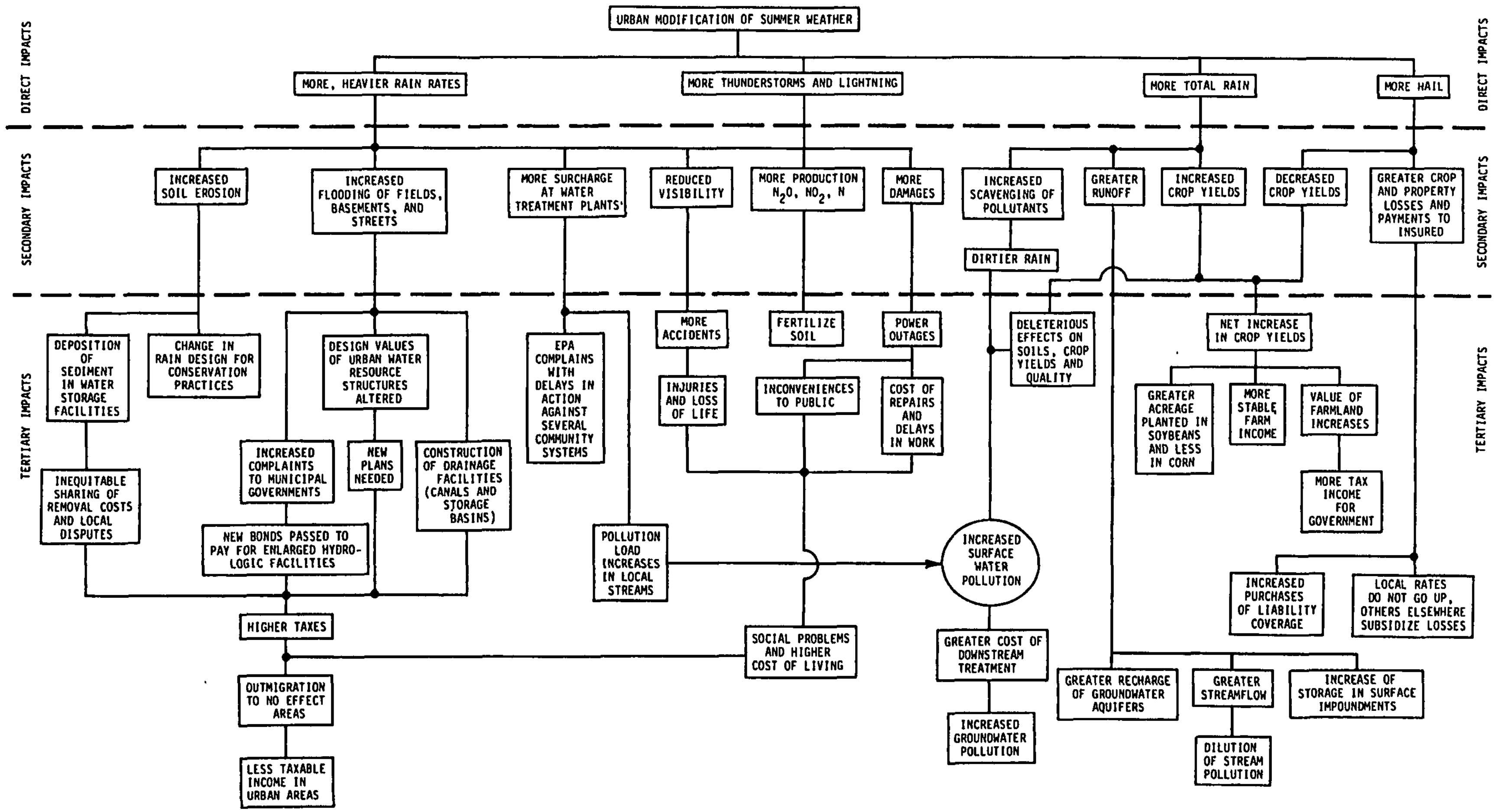


Figure 5. Interrelated impacts resulting from precipitation climate changes caused by St. Louis and Chicago (Changnon, 1981b)

It is well known that the *weather* of Illinois affects many sectors including the construction industry, transportation, business, manufacturing, and energy production and use (Changnon and Lamb, 1990). However, the effects of *climate* change on these sectors in Illinois have yet to be investigated. Human health and safety in Illinois, another weather-sensitive area, has also not been assessed for a change in climate. The effects of altered climate conditions on populations in large cities has been investigated for St. Louis and shows a shift away from warmer urban climates (Changnon, 1992c). Weather extremes such as heavy snows, water-supply droughts, and storm damages also have significant effects on local and state government agencies (figure 6). Sonka (1979) noted the economic impacts on cities in the altered climate area east of Chicago including effects on construction, recreation, and city taxes.

STUDIES OF ADJUSTMENT AND ADAPTATION TO CLIMATE CHANGE

There have been a few studies of adaptation by individuals and institutions to future changes in climate in Illinois. These studies have generally focused on the agricultural sector, certain urban activities, and water management. Easterling and Changnon (1993) studied the effects of three climate scenarios on Illinois corn producers, and ascertained the forms of adjustments and ensuing adaptations that could occur (table 9). They found that producers would make a variety of adjustments as climate change began to develop, and if the change became severe, major changes would occur such as shifting of crop types and widespread use of irrigation. However, the type of adaptation would depend greatly on external economic conditions in other grain-producing areas and ultimately the value (or price) of corn.

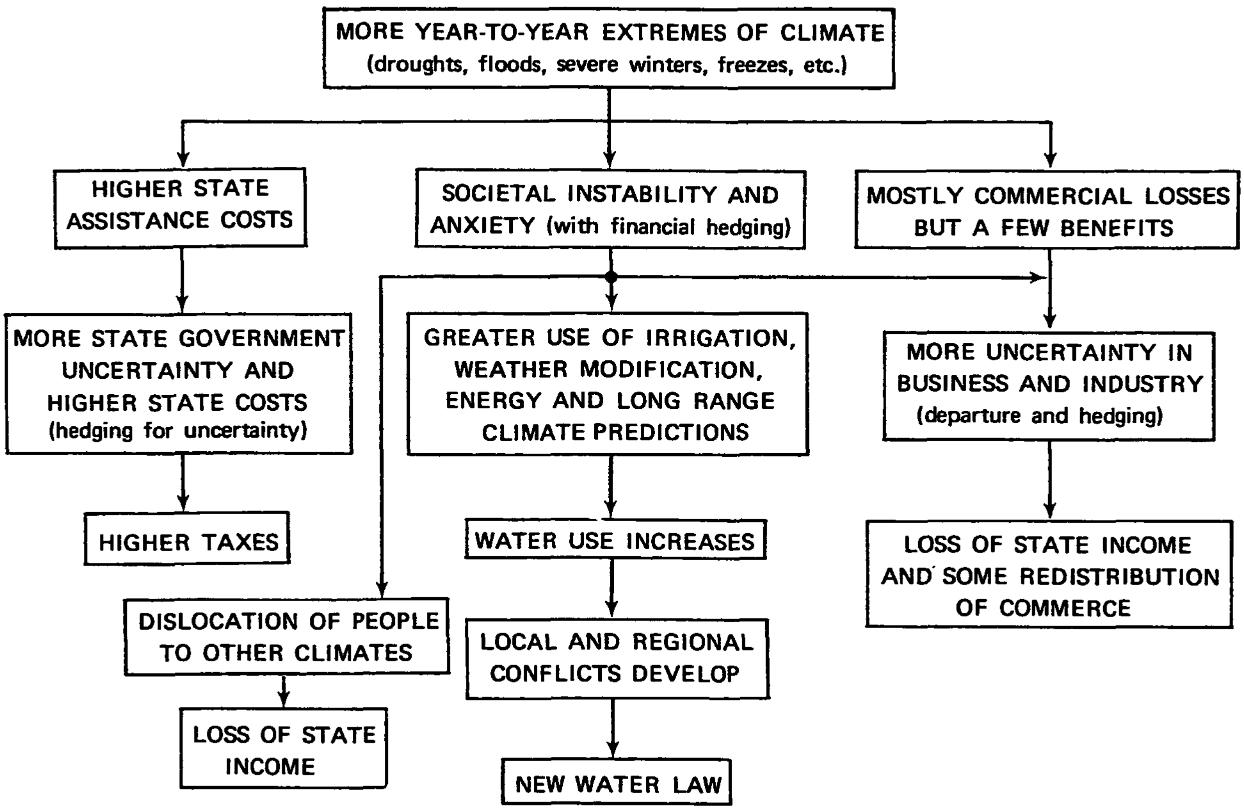


Figure 6. Some of the impacts noted due to short-term climate extremes in Illinois since 1950, and possible adjustments

Table 9. The Estimated Adjustments (Early Phase of Reacting) and Adaptations (Later Reactions) of Illinois Corn Farmers to Climate Change (Easterling and Changnon 1993).

Adjustments to production practices	Adaptations to production practices
• alter planting dates	• install and use irrigation systems
• shifts in crop mixes	• shifts to short-season com
• alter tillage practices	• shifts to sorghum
• alter fertilizer applications	• remove of marginal land from production
	• use weather modification

The potential for widespread irrigation to sustain Illinois agriculture has been investigated. Bowman and Collins (1987) assessed potential areas for irrigation in Illinois or 62 percent of all planted acreage. More than 10,000 square miles in central and northern Illinois could be irrigated successfully on suitable soils and with ground water using pivot irrigation systems (Changnon, 1992b). Petersen and Keller (1990) also predicted the widespread advent of irrigation throughout Illinois and surrounding states under more strenuous climate changes. Changnon (1992b) also assessed the possible impacts of climate change on the seed industry, and included planning recommendations for the seed industry, including the breeding of hardier varieties.

Changnon (1981b) and Sonka (1978) have investigated the agricultural effects of a changed climate east of St. Louis and Chicago where the cites have produced more growing season rainfall and more damaging storms. These studies showed mixed impacts and adjustments. The altered growing season weather (more rain, more storms) had created more crop hail losses, but had led to a net increase in crop yields, and enhanced land values in the affected region. Sales of crop insurance had risen. Schwartz (1992) noted that adaptations were possible in commercial timber areas in Illinois by altering the species planted.

The ever-constant change in Illinois agriculture (Holt, 1992) helps suggest that it can likely react successfully to future climate fluctuations so that corn and soybean production continue at present levels and so that there are no major food shortages. Onal and Fang (1991) and Onal (1992) concluded that economic shifts would vary according to the magnitude of the changed climate and that Illinois agriculture would successfully adjust. Their studies showed adjustments involving an increase in the planting of soybeans and wheat and a decrease in the planting of corn. However, nothing is known about the potential effects or adjustment capability of Illinois' large agribusiness sector.

Certain studies have described potential adjustments and adaptations for the water management area. For example, in the study of lakeshore effects due to lower lake levels, Changnon et al. (1989) showed how an early awareness of a potential climate shift could lead to changes in water management structures, making them more flexible and capable of handling climate-related changes, as a part of normal replacement activities. The problems related to the potentially altered levels of Lake Michigan could all be addressed by engineering works, with the primary issue being who will pay for the costs of their implementation (Changnon, 1993a). Changnon (1988b) also assessed how the impacts of climate change on water resources translated into policy adjustments for a Congressional group. Figure 5 shows how certain adjustments to local climate change were made in the St. Louis area.

Managers of water-supply systems in Illinois have responded to reduced water supplies during previous droughts (Changnon and Easterling, 1989). These responses include temporary measures (adjustments) and permanent measures (adaptations) such as new and larger reservoirs created by modifying spillways and dam heights. There is a lack of knowledge about climate effects on ground water and any form of adjustment that might be necessary, such as how to manage sizable increases in pumpage of ground water to irrigate corn.

The effects of drought and climate change on water-related institutions have also been identified (Changnon, 1989b). The Illinois Water Plan Task Force (1982) identified drought and climate change as major future issues facing Illinois water resources. Consequently, a standing Drought Committee was established with representatives from various state agencies to monitor drought and initiate action as needed.

A third area of climate adaptation-related research has focused on the state's major urban areas, the Chicago and the St. Louis regions. Some studies of the altered climates in local regions due to the effects of Chicago and St. Louis on weather have shown how the local cities have adapted to increased flooding and to detrimental effects on transportation systems, as shown in figure 5 (Changnon, 1981b).

Two studies relating to the national management of floodplains and the national management of droughts are relevant to Illinois. The study of floodplain management issues, done in the context of climate change, revealed many existing problems related to floods and floodplain management, which need to be solved whether or not climate change occurs (Changnon, 1993b). An assessment of drought management nationally identified a series of seven major problems that have not been solved (Changnon, 1992e). These include the difficulty in defining the onset of drought, its infrequency compared to periods when resource managers are in office and experienced, confusion over use of short-term fixes versus long-term, more permanent responses, and the ever increasing social vulnerability to drought. Drought management continues to be inadequate for these and other reasons, and again, many of these problems need to be resolved whether or not a climate change occurs. A change towards a drier regime may well exacerbate drought severity and only magnify the need to solve existing problems in drought management (Changnon, 1992e).

Davis (1991) assessed potential legal issues due to climate change. These issues included changes in existing regulations and laws governing water uses, new laws designed to adapt to climate change, and laws designed to control emissions of trace gases.

DETECTING CLIMATE CHANGE

There are many scientific uncertainties surrounding the climate change issue. Consequently, it is imperative to detect the onset of climate change and also to measure its type and magnitude for Illinois. This task is made difficult by the lack of quality historical records, particularly for weather-sensitive environments, as a basis for assessing historical and future conditions. And the problem is further compounded by the large natural variability of weather conditions experienced in Illinois (Changnon, 1990; Wendland, 1990).

A major issue in the climate change arena is whether climate change has begun, and if not, how might it evolve in the future? The severity of the 1988 drought with high temperatures across much of the nation caused a few scientists to suggest that the drought was an indication of the beginning of a change in climate due to the greenhouse effect. The issue received wide national attention and focused the nation on the key question: could a climate change occur? As noted earlier, there is a great difference of opinion among scientists as to whether a greenhouse-induced climate change has begun.

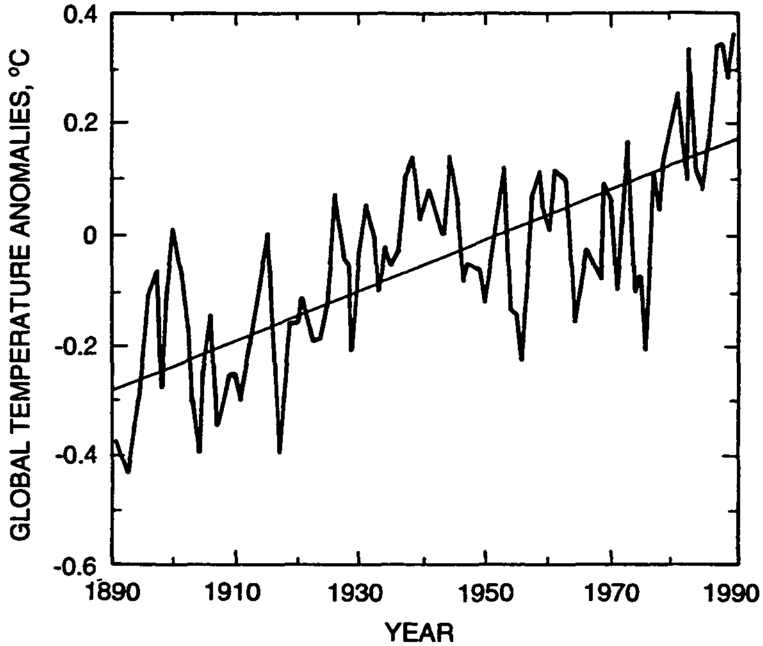
Has Greenhouse-Induced Climate Change Begun?

The many warm years during the 1981-1991 period prompted some scientific belief that global warming had begun and was being reflected during the warmest decade of the past 100 years, both globally and in the Midwest. Other scientists, however, indicated that the range of temperatures of the 1980s was well within the limits of past natural climate variability and hence not indicative of a shift caused by the enhanced greenhouse effect.

A more central issue is whether the conditions over the last 100 years, when rapid increases in atmospheric CO_2 occurred, reflect a greenhouse-induced climate change. Figure 7 depicts the behavior of global temperatures and precipitation over the past 100 years. Basically, the temperatures show an overall warming trend. If the curve is dissected, however, there is a warming trend from 1890 until the 1930s, a cooling trend until the 1980s, and then a resumption of warming. Much of the noted warming is in the form of low or nocturnal temperatures, not in the daily high values. This suggests, and historical records support, an effect due to increasing cloud cover. And yet precipitation trends for the globe indicate a general increase. Do these features support or refute a change of climate due to the greenhouse effect?

Over the past 100 years the atmospheric equivalent of CO_2 levels increased about 20 percent, from about 290 to 350 parts per million. This increase, when synthetically introduced into climate models, predicts a global warming of at least 2.7°F, a reduction in the diurnal temperature range, a 5 percent increase in global precipitation, some increase in cloudiness, and an increase in sea levels. Balling (1992) indicates that the increases in cloud cover and in precipitation since 1890 are consistent with what the climate models indicate from a CO_2-enhanced environment. Although the

Global temperature anomalies (based on 1950-1979 normals) for the period 1891 -1990. Data preparation is described by Jones et al. (1986c); actual data are available in Boden et al. (1990).



Annual precipitation index for land surfaces of the globe for the period 1891-1986. Values are means of percentiles for grid points around the globe (e.g., 0.50 is an average precipitation value, 0.45 is below average, and 0.55 is above average). Data are from Diaz et al. (1989).

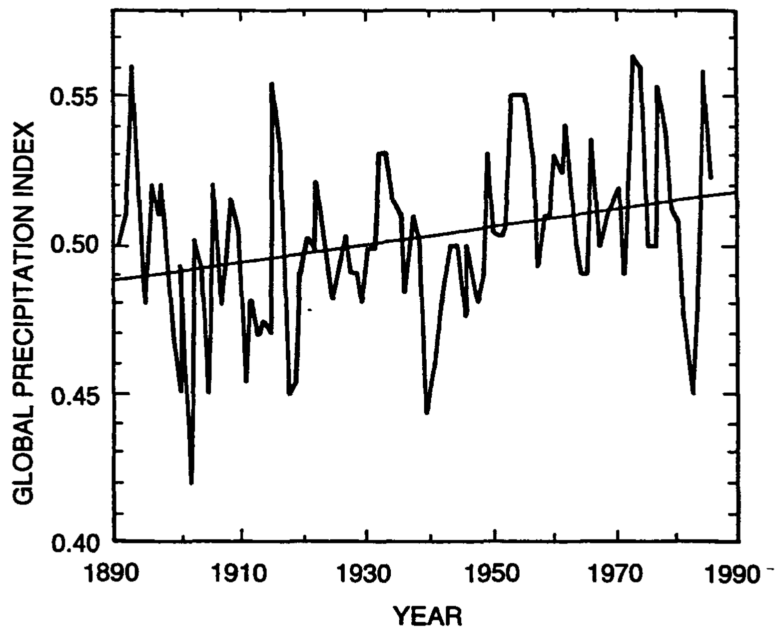


Figure 7. 1890-1990 global temperatures and precipiation index (Balling, 1992)

temperatures increased, the increase of 1.3°F was less than predicted, as was the sea-level rise. The dampening of the diurnal temperature range was considerably greater than models predicted. Balling concludes that we have been experiencing the unfolding of the greenhouse effect, but that the evidence for change is not pointing towards a climatic disaster. The changes estimated by most GCMs indicate the greatest warming would occur at the higher latitudes, but the global warming over the last 100 years has not been at these higher latitudes, thereby tending to refute the greenhouse effect.

Temperature changes in Illinois, the Northern Hemisphere, and the world over the past 100 years can be due to many other effects. These include four forms of contaminated records. For example, there have been changes in instruments and relocations of weather stations that have altered, potentially in a systematic way, temperature and precipitation records. Furthermore, most of the weather measurements have been concentrated on land, which is only 30 percent of the earth's surface. Thus, there is a bias in the measurements, and they may or may not represent global values. A third contaminant relates to the "urban heat island" (Changnon, 1992c). Many of the weather stations of 1890 were in communities that grew during the next 100 years. Since urban areas act to increase temperatures, many locations exhibited local warming that increased over time. A study of the urban heat island effect led to the conclusion that approximately 0.5°F of the observed global warming over the last 100 years has been due to that effect.

Records have also been contaminated by desertification, generally due to the overgrazing of marginal arid lands in North America, Africa, and Asia. This change in the surface altered the albedo and caused a warming over time in these large regions. The regional warming over the past 100 years is estimated at 1.3°F with an effect on global temperatures of 0.3°F. In general, these human-induced contaminants of the historical record, principally the urban heat island and desertification, have accounted for an estimated 0.8°F wanning over the past 100 years (Balling, 1992).

There have been other nongreenhouse effects on the climate over the past 100 years. Although variations in solar influences could have occurred, this is not well established. There are also potential influences due to volcanic activity and the dust injected into the upper atmosphere could lead to temporary cooling. Most important of these nongreenhouse effects is the rapid increase in pollutant-generated aerosols, particularly sulphate aerosols. Since 1950, sulphate aerosol concentrations have increased greatly, principally in the Northern Hemisphere, which has led to additional clouds, more precipitation, and potential decreases in temperature over the last 40 to 50 years. In fact, the aerosol sulphate influence may be responsible for the decrease of the global temperatures after 1940 (Balling, 1992).

In trying to answer the question of whether the climate behavior over the last 100 years reflects the greenhouse influence, one must assess the aforementioned effects of atmospheric aerosols, urban heat islands, and desertification (representing changes of roughly 1.3°F) in addition to those proposed from CO_2 increases (roughly 2.7°F). By subtracting 1.3°F from 2.7°F, one has 1.4°F of warming due potentially to the enhanced greenhouse effect. This is approximately the value that has been observed in the 100-year record. These adjustments suggest that enhanced greenhouse effects already may have begun. However, many scientists see the climatic behavior of the past 100 years as being well within the random natural variations of climate and not indicative of the greenhouse effect. Good examples of natural climatic fluctuations of the decadal scale include the Midwestern drought during the 1930s and the extremely high water levels of the Great Lakes due to excessive wet periods in the 1970s and early 1980s. Mahlman (1992) argues that until such decadal-scale fluctuations are better understood and predictable, it will continue to be difficult to diagnose the specific signals of permanent climate change. Moreover, detecting climate change becomes ever so much more difficult when assessing conditions in smaller regions such as Illinois.

Possible Dimensions of a Future Climate Change

Various techniques have been employed to ascertain the future development of a greenhouse-induced climate change so as to detect its initiation or to confirm its existence. Primary among the techniques used have been the outputs from climate models. However, climate analogs using historical climate data have also been developed (Changnon, 1991a). Figure 8 shows various examples of future change generated by GCMs. One graph (figure 8a) depicts the global temperature values from 1860 to the 1980s, and then presents curves from three different climate scenarios (Schneider, 1990). Note that the lower scenario appears to be an extension of the general upward trend from the existing data of the past 100 years. Several climate models have been used in climate transition experiments to ascertain the future evolution of climate conditions. Figure 8b presents the expected decadal changes over a 100-year period in globally averaged surface temperatures derived from GCMs. The curves all indicate warming but at different rates so that 80 years into the future they are indicating between 4.0° to 6.7°F warming. Figure 8c depicts the precipitation change over time, as developed from a transient CO_2 experiment with a climate model for Spain. This depicts the expected fluctuations in precipitation, developed from two different methods.

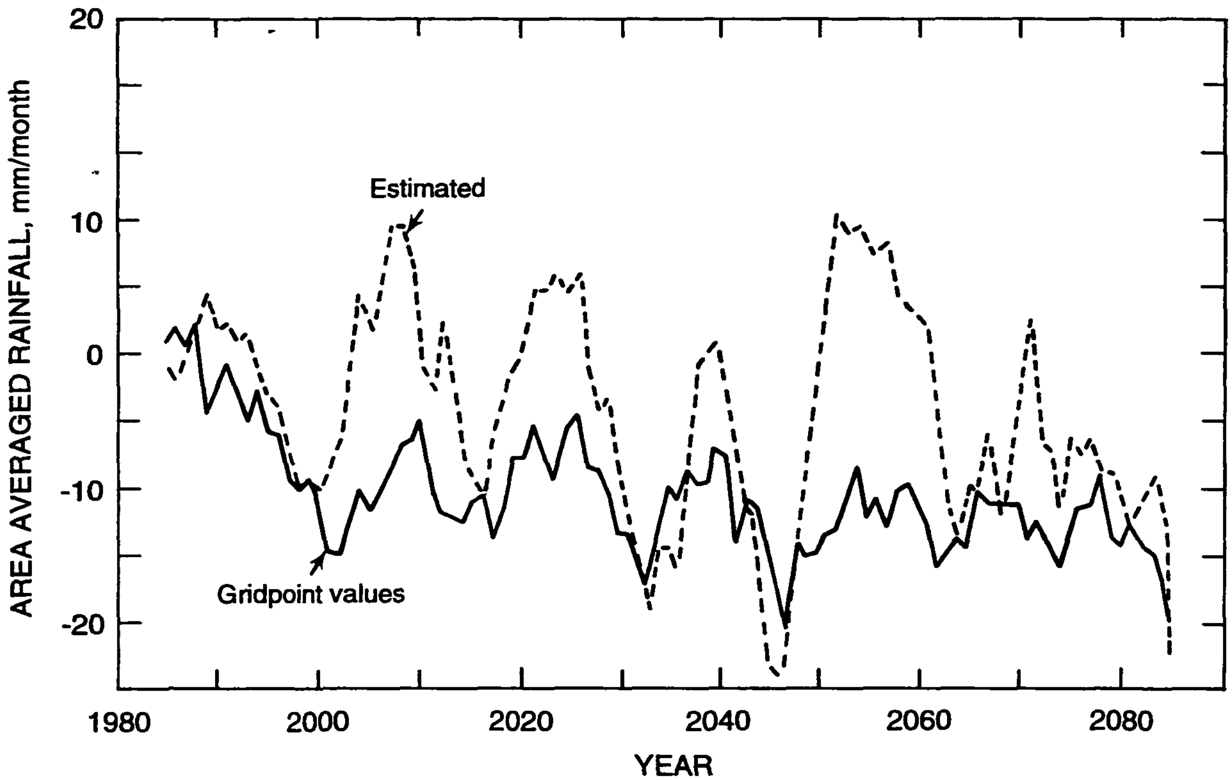


Figure 8. Transition of future precipitation in Spain from a transient CO_2 test

The Intergovernmental Panel on Climate Change or IPCC (1992) used various climate scenario conditions, and climate models, to express the potential range of future temperature changes after 1990. The upper graph in figure 9 is the IPCC's "best-estimate temperature changes" derived from six climate scenarios based on the Panel's "best estimate" of climate sensitivity. The climate effects of sulphate aerosols and ozone depletion have not been taken into account, and both would tend to alter the rate of warming.

The lower graph in figure 9 from Mahlman (1992) illustrates the sizable problem in detecting greenhouse warming. In this schematic, the comparison of a natural signal of change over a 100-year period is superimposed with a warming trend and a series of fluctuations, and the actual warming trend will not be smooth. It will take many years to separate a fluctuating greenhouse signal, shown as $T_{a,}$ from the undisturbed fluctuations, signal T_u.

Another approach for detecting future climate change is through use of statistical analyses of historical data combined with future data as time progresses. Karl et al. (1991) performed a statistical analysis of the Midwestern historical climate data, and compared the past variability of climate with the range of outputs from GCMs to ascertain how long it would take to detect climate change with high statistical significance, the types of climate changes being estimated for the Midwest. Their results indicated that for the range of temperature changes predicted, it would take 10 to 20 years of change before there could be a high degree of certainty about changes in surface air temperatures. Their results also indicated that 30 to 40 years would be needed for certainty in detecting the type of precipitation changes being predicted by GCMs.

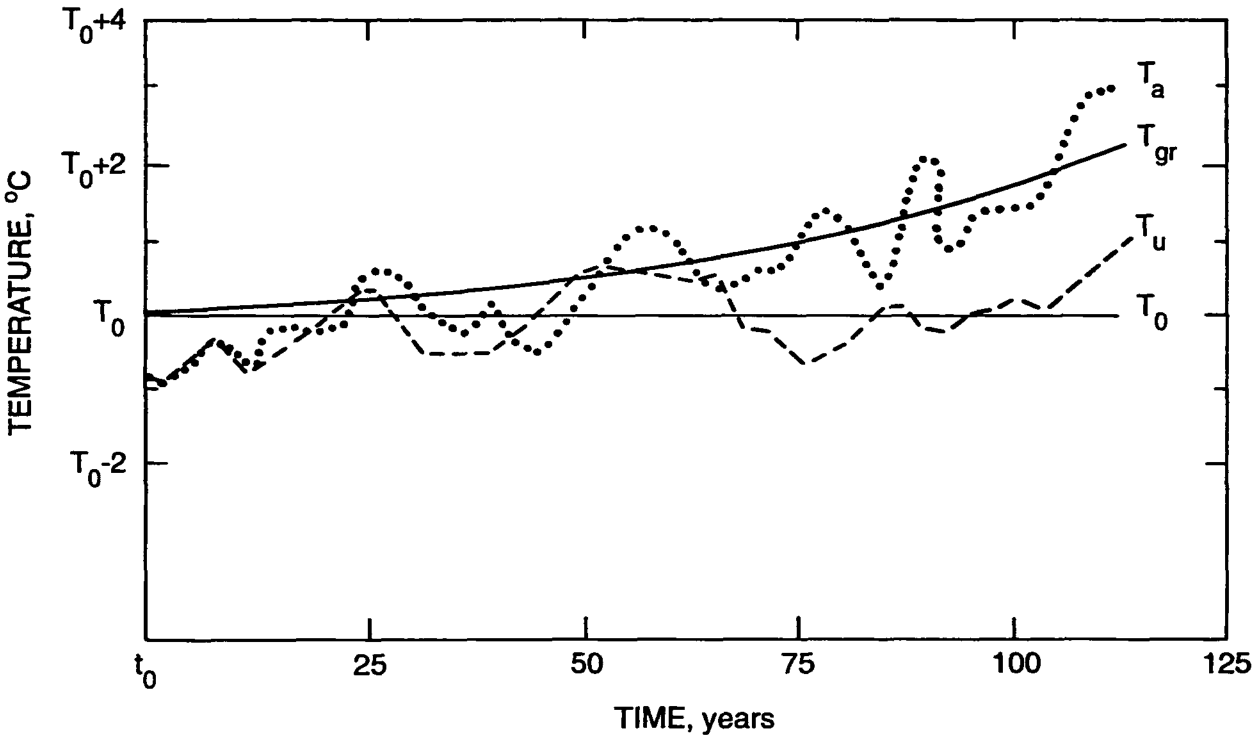


Figure 9. Schematic used to illustrate the problem of detecting a change in climate (Mahlman, 1992)

A third aspect of detecting future climate change, beyond use of the outputs of GCMs and statistical analyses of past and future data, is the use of new and more sensitive means of measurement to sense the change. Changnon (1992d) addressed the issue of using data from new weather radar systems being installed in the 1990s as a means to better detect future shifts in rainfall. The Illinois Global Climate Change Program (Changnon, 1991b) identified ten types of measurements in Illinois that could be useful in detecting future change by continuing the Illinois Climate Network, and establishing "benchmark" weather stations and stream basins with varied physical measurements to detect subtle shifts in areas such as streamflow, surface water temperature, and ground-water levels and temperatures. Unfortunately, very little has been done to develop new techniques for sensing such changes or to study historical shifts in climate-sensitive systems.

An extremely critical issue is the detection and measurement of future climate change, whether through direct measurements of the climate phenomena or indirect measurements of the effects of change in hydrologic or biological systems.

SUMMARY

Review of the published literature reveals much less is known about future climate change in Illinois than is known. First of all, there is uncertainty about the dimensions of the future climate of Illinois. This uncertainty translates into only limited knowledge about the range of effects that future changes in climate could produce in Illinois. The problem of assessing climate change also includes the uncertainty among atmospheric scientists about the future climate as well as an inability to predict climate change with accuracy at the regional level. Tables 10 and 11 highlight what scientists do and do not know about climate change in Illinois.

Table 10. What Is Known about CO_2 -Induced Global Climate Change in Illinois

Atmospheric conditions

- Atmospheric CO_2 content is increasing 0.5 percent per year.
- Increases in CO_2 and other trace gases will lead to global warming if all other climatic controls (e.g., solar input) remain constant.
- A majority of atmospheric scientists believe that global warming will occur at some level, but a minority of atmospheric scientists do not agree.
- Output of most GCMs run with a doubling of CO_2 indicate the resulting climate of the Midwest would be considerably warmer, with either an increase or decrease in the annual precipitation and with redistribution of the precipitation, generally leading to warmer, wetter winters and hotter, drier summers.
- Sulfate aerosols in the atmosphere tend to negate the warming effect.
- More thunderstorms occur, but they are generally less severe storms with less heavy rainfalls.
- The growing season is longer with more hot days and overall higher evapotranspiration.

Partially quantified effects of wanner, drier climate

- Corn and soybean yields shifted, generally to lower levels.
- There are decreased streamflows and lower ground-water levels.
- Less surface water resources are available.

- A wide range of costs are associated with modification to the Illinois-Lake Michigan shoreline and the diversion at Chicago.

Adaptation to warmer, drier climate

- All climate scenarios indicate that there will need to be farm-level adjustments and adaptation..
- Adaptation of Chicago shoreline facilities and water management structures is expensive but possible.
- Some tree species may be lost if climate change is rapid.
- Local and state governments would incur higher costs to pay for research and changes in infrastructure.

Table 11. What Is Not Known about CO_2-Induced

Global Climate Change in Dlinois

Atmospheric Conditions

- It is unresolved whether the past 100 years' climate reflects any global warming signals.
- The degree of global wanning would be highly variable (1.5° C to 4.5°C).
- The evolution of the climate change is uncertain, ranging from a relatively smooth, slow transition to a disorganized series of abrupt changes.
- Potential shifts in regional climates are poorly understood and ill-defined.

Unquantified impacts or ones not well understood

- The effects of additional atmospheric CO_2 on large-scale crop production are unknown.
- The effects of climate change on livestock and Illinois agribusinesses are unknown.
- The effects of climate change on water quality are unknown.
- The effects of climate change on most plant species are unknown.
- The effects of climate change on the construction industry and recreation are unknown.
- The effects of climate change on government agencies and large urban areas of the state are unknown.
- The effects of climate change on human health and welfare are unknown.

- The effects of climate change on large urban areas, river basins, or the Great Lakes are unknown.

Adaptation

- Adaptation by Illinois businesses and industries has not been investigated.
- Methods of adapting involving institutions and various laws relating to water and the environment are unknown.
- Adaptation by most plants and crops is unknown.

We also lack historical data in many weather-sensitive areas, limiting the development of relationships between varying climate conditions and our environmental and economic systems. If the climate of the future is different than anything experienced in the past 100 years, use of statistical-physical relationships based on the past will be unable to predict those of the future. Finally, the amount of research attention devoted to measuring and detecting change, and to the possible adjustments of climate change in Illinois has been meager.

Past studies of Illinois' climate and its influences have revealed certain important things which are relevant to understanding climate change. They follow.

1. Humans have changed the climate of Illinois, at the local scale (largely due to cities) and at the regional scale (due to the addition of air pollutants from surface sources and jet aircraft).
2. Geological and other records indicate that the past climates in Illinois have undergone major fluctuations, having been much colder and warmer and wetter and drier than today's climate. The current climate is in a relatively warm regime, compared to the climate of the past 100,000 years. The climate is always varying over periods lasting from a few years up to a century, but a changed climate is a prolonged shift lasting from several centuries to several thousands of years.
3. A greenhouse effect exists globally. It will be amplified by ever-increasing additions of trace gases. Additions of CO_2 are continually increasing the atmospheric content of CO,.

4. Historical warm periods on the earth have been associated with historical periods of relatively high CO_2, helping to give credence to the belief that additional CO_2 in the atmosphere will be related to global warming.

5. Past behavior indicates that the future climate will somehow be different from climates of the past 30, 50, or 100 years.

6. Illinois is a major source of CO_2 and of sulfate aerosols.

Several atmospheric unknowns are equally critical to understanding climate change in Illinois. They follow.

- The climate changes for Illinois predicted by global climate models differ from model to model. They all suggest a warmer, somewhat drier environment (at least in some summer months), but the differences between the models is very large for the Illinois area.
- It is unclear how increased trace gases, additional sulfate aerosols, and natural controls on the climate will interact in the future, but "climate surprises" well beyond GCM predictions are likely.

Beyond these known and unknown areas related to the atmospheric sciences dimension of the climate change issue, there is the equally broad question about known and unknown effects of various changes in climate. With uncertainty in the type of future climate, several climate scenarios related to the Illinois area have been developed and tested in impact studies. Some of these studies have been derived from GCMs, while others have been analogs derived from historical periods, such as droughts and wet periods, combined in various climatologically consistent ways.

Qualitatively, we can crudely estimate the effects of varying climatic extreme periods, such as hot and dry or cold and wet, on many of our natural systems, economic sectors, and human behavior. However, quantitatively, this assessment reveals that we know very little about the range of effects in Illinois. Much of what has been studied relating to possible effects of climate change has been in two areas: water resources and agriculture. Information in agriculture relates primarily to the range of effects on corn and soybean yields, and the ensuing range of economic impacts to farmers and the state. The dimensions of the economic impacts are limited by the scenarios tested and by the extent of the research.

In the water resources area, estimates of potential effects have come largely from studies of historical analogs of extreme periods such as the 1930s and 1950s. Some climate scenarios tested produce fairly significant changes in streamflow with ensuing problems with surface water supplies. Changes in storm activity, flooding, and droughts can be expected in drier periods. An assessment of effects due to lower levels of Lake Michigan on Chicago's shoreline and diversion produced a range of negative economic impacts.

Some of the climate change research has addressed potential adaptations to the impacts, as estimated from climate scenarios. This research has illustrated a variety of ways to adjust and adapt to climate change in Illinois agriculture, including the potential for developing widespread irrigation. Similarly, adjustments to handle lower lake levels and reduced streamflows appear possible for water management. The results on adaptation to climate change, albeit limited, indicate there are many ways to adapt to most of the estimated climate changes through new technologies, energy conservation, use of new crop varieties, institutional changes, and mostly through increased expenditures. In essence, society can adapt but it will be costly. There needs to be additional research because we know very little about adaptation in our institutions and legal systems. The sooner we begin adaptative planning, the lower the ultimate cost will be.

The areas in which there has been little if any study related to the effects of climate change include several well-known weather-sensitive systems. Some of the more significant ones as yet unstudied, or ill-defined, include 1) effects of altered climates on water quality, including the assimilation of wastes and the effects on fish and other riverine life; 2) effects on agribusinesses in Illinois; 3) impacts on recreation and tourism; 4) changes in energy use and production; and 5) impacts on construction, businesses, and the manufacturing industry. Similarly, there are no estimates on ways in which these sectors and systems could adapt.

Meager knowledge exists about the impacts of climate change on local and state agencies that deal with weather-induced problems. Would a given climate change be less costly or much more costly than current expenditures by the state of Illinois?

To effectively deal with the issue of climate change, it is necessary to detect and measure the onset, magnitude, and type of change. Many existing weather measurements are generally inadequate to detect the change. Past human influences and poor instrumentation make study of historical data from most existing measurement systems difficult, and the results are questionable. Further research is necessary, with monitoring systems installed in pristine areas that can be protected and maintained over decades.

The plan for an Illinois Global Climate Change Research Program (Changnon, 1991b) identified three regions for study with research involving a multidisciplinary integrated assessment approach that comprehensively examines (1) the range of physical environmental effects, economic impacts, and social reactions to climate change, (2) impacts on human health, and (3) adaptation mechanisms. The highly weather-sensitive areas identified include the Great Lakes basin, the Chicago metropolitan area, and the Illinois River basin. Plans for developing such comprehensive research programs have been initiated for the Great Lakes basin (Changnon 1992f) and for the Chicago area, but research has not begun due to a lack of funding. Such endeavors require a diverse group of scientists and engineers working together over several years and with substantial funding.

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A Division of the Illinois Department of Energy and Natural Resources

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Produced by the Illinois State Water Survey Office of Publications Services.